

# Magic Numbers from New Systematics

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## **Abstract**

A new systematics from the separation energy of deuteron is used to examine the magicity of stable as well as nuclei towards dripline.

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Nuclei with  $N$  (neutron numbers)=2, 8, 20, 28, 50, 82, 126 show unusual stability and hence are called magic nuclei. Similarly  $Z=2, 8, 20, 28, 50, 82$  are also established proton magic numbers. Whether these magicities change for proton or neutron rich nuclei has been a subject of recent interest [1-4]. In course of these works, the well known magicities have been shown to loose their character with increased neutron or proton numbers and some new magic numbers have evolved. These attempts use different systematics; 1) the plot of one and two neutron or proton separation energies, 2) the  $Q$ -value for  $\beta^-$  and  $\beta^+$  decay 3) excitation energy of the 1st excited state and 4) the energy of alpha particle for examining the magicity of nuclei. There are also indirect methods such as calculating the shell gap from two nucleon separation energy. The different systematics have normally agreed in case of well known magic numbers but there are some differences when one comes to the cases of not so well known magic numbers. For example in Ref[4]  $N = 16$  has been shown to be a magic number for  $T_z = 3, 5/2, 7/2$  ( $Z = 9, 10, 11$ ) from breaks in 1-neutron separation energy plotted against odd neutron numbers for a given  $T_z$ . This magic number is later confirmed from  $Q_{\beta^-}$  systematics for  $T_z = 5/2, 7/2$  only [3]. In ref[1] on the other hand the authors plot the 1-neutron separation energy against all  $N$  (both even and odd) at a given  $Z$  (both odd and even). They conclude from comparison with a model that  $N = 16$  magicity appears only at  $Z = 7, 8$  and not at  $Z=10$  ( $T_z = 3$ ) or  $Z = 9, 11$ . The authors of [1-3] also discuss a number of new magic numbers towards the dripline from their respective systematics.

In this paper we present a new systematics to investigate the indication of magic numbers. The separation energy of deuteron ( $S_d$ ) is plotted against nucleon numbers and the breaks in the systematic trend indicate magicity. No nuclei in it's ground state have been observed to decay by deuteron emission (Neither do any nuclei show negative deuteron separation energy). Recent calculations also do not support nuclei having minimum energy configuration with a deuteron [5]. However, the ground state of the nucleus  ${}^6\text{Li}$  for example is well described by the  $d + \alpha$  cluster structure [6]. Experimental studies of  $\alpha$

knockout reactions [7] and back angle increase of  $\alpha$  elastic scattering cross-section from  ${}^6\text{Li}$  [8] also support it's deuteron substructure. In Ref. [8], the possibility of  ${}^6\text{Li}$  (in which the deuteron is loosely bound and it's separation energy is smaller than neutron and proton separation energy) as a deuteron-halo nucleus has been discussed. The separation energy plots (in which the odd-even staggering in mass plots is doubled) of deuteron have also been utilised earlier to exhibit the np pairing in light odd-odd nuclei [9]. This motivates us to use the plot of deuteron separation energy to investigate magicities near and away from the stability line. For traditional magic numbers we see that the breaks in  $S_d$  are rather striking and are easily indicative. For not so striking indications we follow the following prescription: If the separation energy of deuteron at any odd neutron number say ( $N$ ) falls below the line joining the  $N - 2$  and  $N - 4$  nuclei then the isotope with  $N - 1$  is magic or extra stable. If on the other hand  $S_d$  is above the line, magicity is quenched. This prescription is also applied to indicate proton magicities.

The separation energy is defined as

$$S_d(N, Z) = B(N, Z) - B(N - 1, Z - 1) - B_d \quad (1)$$

where the binding energy of two nuclei and deuteron are involved. In fig. 1 we show the deuteron separation energy as a function of  $N$  at specific  $Z$  values. We choose  $Z$  values in such a way so as to scan the well known neutron magicities. We do not include in our plots the systematics predicted values and show only the experimental data points. All the experimental masses required for our calculations are adopted from the latest mass table of Audi and Wapstra [10]. The very well known magicities of  $N=2$ ( $Z=4$ ),  $N=8$ ( $Z=8$ ),  $N=20,28$ ( $Z=20$ ),  $N=50,82$ ( $Z=50$ ) and  $N=126$ ( $Z=82$ ) are clearly indicated by the new systematics. The separation energy has a increasing trend when plotted against neutron numbers unlike the decreasing trend of the 1n-separation energies. This makes it easier to observe the extra downward shift of  $S_d$  at  $N = N_M + 1$  (where  $N_M$  is a neutron magic number). For  $Z=30$  since no magic neutrons numbers are encountered, the

systematics do not show any break. In fig. 2 we show the well known proton magicities from the plot of separation energy against proton numbers at fixed neutron numbers. The  $Z=8(N=8,16), Z=20(N=24), Z=50(N=65), Z=82(N=102,126)$  are clearly visible from the new systematics. The loss of some of the well known neutron and proton magicities with neutron or proton numbers are also studied. The loss of  $N=8$  magicity at  $Z=4$  could be seen from fig.1. According to the  $Q_{\beta^-}$  systematics[3]  $N=20$  vanishes at  $T_Z \geq 7/2 (Z \leq 13)$  and according to [1] the  $Z$  region is  $Z = 11 - 14, 18, 22 - 24$ . In this work we find that  $N=20$  magicity vanishes at  $Z=10-12$  only and is present at  $Z=13$  (fig.3),14 (fig.4). In the  $Z=22-24$  region we could not conclude about the behaviour of  $N=20$  magicity due to unavailable data points in the literature. Disagreement with [1] is found for  $Z=18$  (fig.3) where no quenching was observed for the  $N=20$  magic number. The  $N=28$  magicity is shown to loose its character at  $T_Z \geq 5 (Z \leq 18)$  from the  $Q_{\beta^-}$  systematics [3] and at  $Z=17,25,26,30$  from [1]. We find that this magicity is absent at  $Z=16$ (fig.4),17,18(fig.3) and 26(fig.3). It is present however at  $Z=25$  (fig.4). For  $Z=30$  and  $Z<16$ ,  $N=28$  magicity could not be examined without systematics predicted value.

The  $Z=8$  magicity is observed from  $Q_{\beta^-}$  systematics in the region  $N=11,13$  whereas [1] predicts a loss of magicity at  $N=11$  in the range  $N=6,10-12$ . We find (fig.3) that the  $Z=8$  proton magic number is quenched at  $N=11$  thereby disagreeing with [3]. The vanishing of  $Z=20$  magicity at  $N=16-18,22-26$  is reported in [1]. This agrees with our systematics for  $N=16$  (fig.2) and  $N=18$  (fig.4). In the  $N=22-26$  region the present systematics agrees with [1] for  $N=22,23$  only ( $N=23$  in fig.3) where the  $Z=20$  magicity is quenched. For the region  $N=24-26$  the magicity though visible is fairly weak (e.g  $N=24$  (fig.2)).

Finally we investigate some of the newly discovered magic numbers in the framework of the present systematics. For example we observe the  $N=6$  magic number at  $Z=4$  (fig.1) in the region  $Z=3-8$  predicted by [1]. Referring to fig.4 we show the  $N=16$  magicity for  $Z=9,10$  which was predicted to be present in  $T_Z \geq 3 (Z \leq 10)$  region by Ozawa et al [4]. The  $N=30$  magicity predicted by [3] is observed in this work at  $Z=26$  (fig.4) only. For the

$Z=14$  magicity quite different  $N$  ranges are suggested in literature. In [3] it is  $21 \leq N \leq 27$  and in [2] it is  $13 \leq N \leq 19$ . From the present systematics we observe this magic number at  $N=16$  (fig.2), 18(fig. 4) which is in the range predicted by [2]. The new magic number at  $Z=16$  predicted in the range  $N=21-27$  by [3] is observed from the new systematics at  $N=22-27$ (fig.3) but is found to be absent at  $N=21$ . Some of the discrepancies of different magic numbers and their behaviour away from the stability line are summarised in Table 1. This shows the importance of deuteron separation energy systematics in the proper prediction of magic numbers and their behaviour. Therefore,in order to obtain a complete picture the present systematics along with other systematics must be considered.

In addition to the already observed magicities by the new systematics we observe a magic like behaviour of  $N=26$  at  $Z=13$  and 14 (fig.3). We also see indication of extra stability for  $N=26$  in P,S (fig 4) and Cl. A pseudo shell closure at  $N=26$  is reported for Cl,S,P isotopes from mass measurements at GANIL and Dubna [11]. The break in  $S_{2n}$  versus  $N$  plot followed by a flattening at  $N+2$  and beyond indicates that  $N$  is a magic number. This break was observed in [11] with the measured mass data for Cl,S,P. However this data confirms the  $N=26$  magicity only for  $Z=16,17$  from the flattening at  $N=28$  in the  $S_{2n}$  against  $N$  plot. The present systematics clearly show the  $N=26$  extrastability for  $Z=13-17$  with the available mass data. Detailed investigation in this direction may be pursued in future.

In this work we present a new systematics from a plot of deuteron separation energy against number of neutrons or protons to investigate the magicity of nuclei. The new systematics reproduces the well known magic numbers. The behaviour of well known magic numbers have been discussed with variation of neutron and proton numbers and in comparison to other established systematics. The newly observed neutron and proton magicities have also been discussed. The present systematics indicates extrability of  $N=26$  for Al to Cl isotopes.

## References

- [1] S. Adhikari and C. Samanta, Int. Jour. Mod. Phys. E, 13 (2004)987.
- [2] C. Samanta and S. Adhikari, Phys. Rev. C 65 (037301)
- [3] R. Kanungo et al, Phys. Lett. B 528 (2002) 58.
- [4] A. Ozawa et al, Phys. Rev. Lett. 84 (2000) 5493.
- [5] R.K. Gupta et al, Jour. Phys. G 28 (2002) 699.
- [6] F. Ajzenberg-Selove, Nucl. Phys. A 490 (1988) 1.
- [7] D.I. Bonbright et al, Jour. Phys. G 3 (1977) 1359.
- [8] Y.T. Oganessian and V.I. Zagrebaev, Phys. Rev. C 60 (1999) 044605.
- [9] D.N. Poenaru and W. Griener, *Handbook of Nuclear Properties*, (Clarendon Press, Oxford 1996) p. 19.
- [10] G.Audi, A.H.Wapstra and C.Thibault, Nucl. Phys.A 729 (2003) 337.
- [11] Z. Dlouhy et al, Nucl.Phys. A 701 (2002) 189c.

**Table 1** Some discrepancy in the behaviour of magic numbers as observed from the present work in comparison to other published works. The abbreviations(l) stands for lost, (q) for quenched, (p) for present and (c.s) cannot say.

Magicity	Ref[1]	Ref[3]	This work
$N=20(l)$	$Z=11-14, 18, 22-24$	$Z \leq 13$	$Z=10-12$ ( $Z=13, 14, 18, 22, 23(p)$ , $Z=24$ (c.s))
$N=28(l)$	$Z=17, 25, 26, 30$	$Z \leq 18$	$Z=16-18, 26$ ( $Z=25, 30$ (p))
$Z=8$	$N=6, 10-12(l)$	$N=11, 13(p)$	$N=12(p), N=10, 11, 13(l)$
$Z=20(l)$	$N=16-18, 22-26$	-	$N=16, 18, 22, 23$ ( $N=24-26$ magicity weakly present)
$N=6$	$Z=3-8$ (Ref.[2])	-	$Z=3, 4, 6$ ( $Z=5(q), Z=8(c.s)$ )
$N=16$	$Z=7, 8$ (Ref.[2])	$Z=9-11$	$Z=7-11$
$N=30$	-	$Z=21, 23$	$Z=26$
$Z=14$	$N=13-19$ (Ref[2])	$N=21-27$	$N=16, 18, 25$ ( $N=21-24(l), N=26, 27(c.s)$ )
$Z=16$	-	$N=21-27$	$N=22-27$ ( $N=21(l)$ )

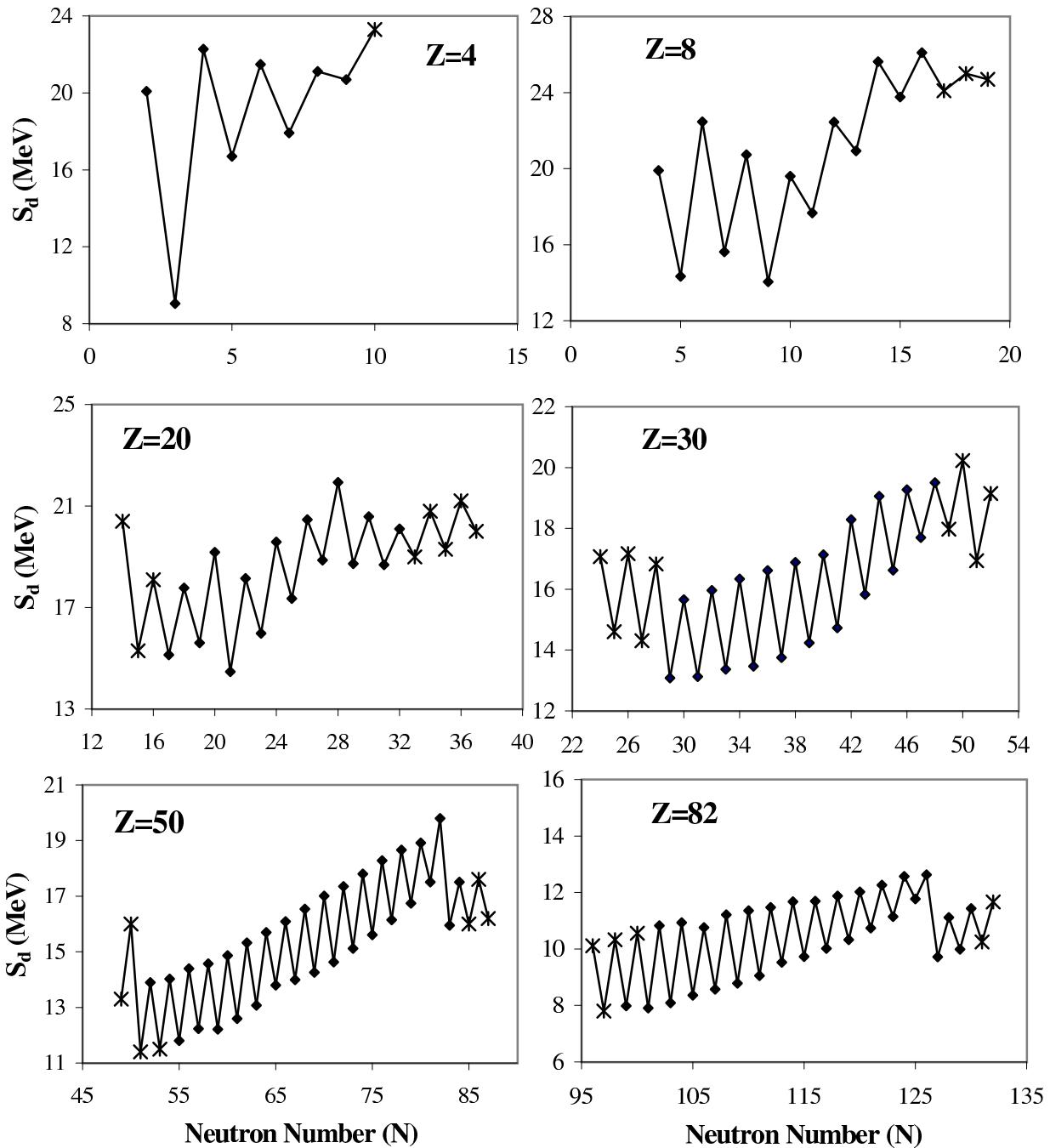


Figure 1: Plot of deuteron separation energy against neutron numbers at specific proton numbers indicated within the figures.

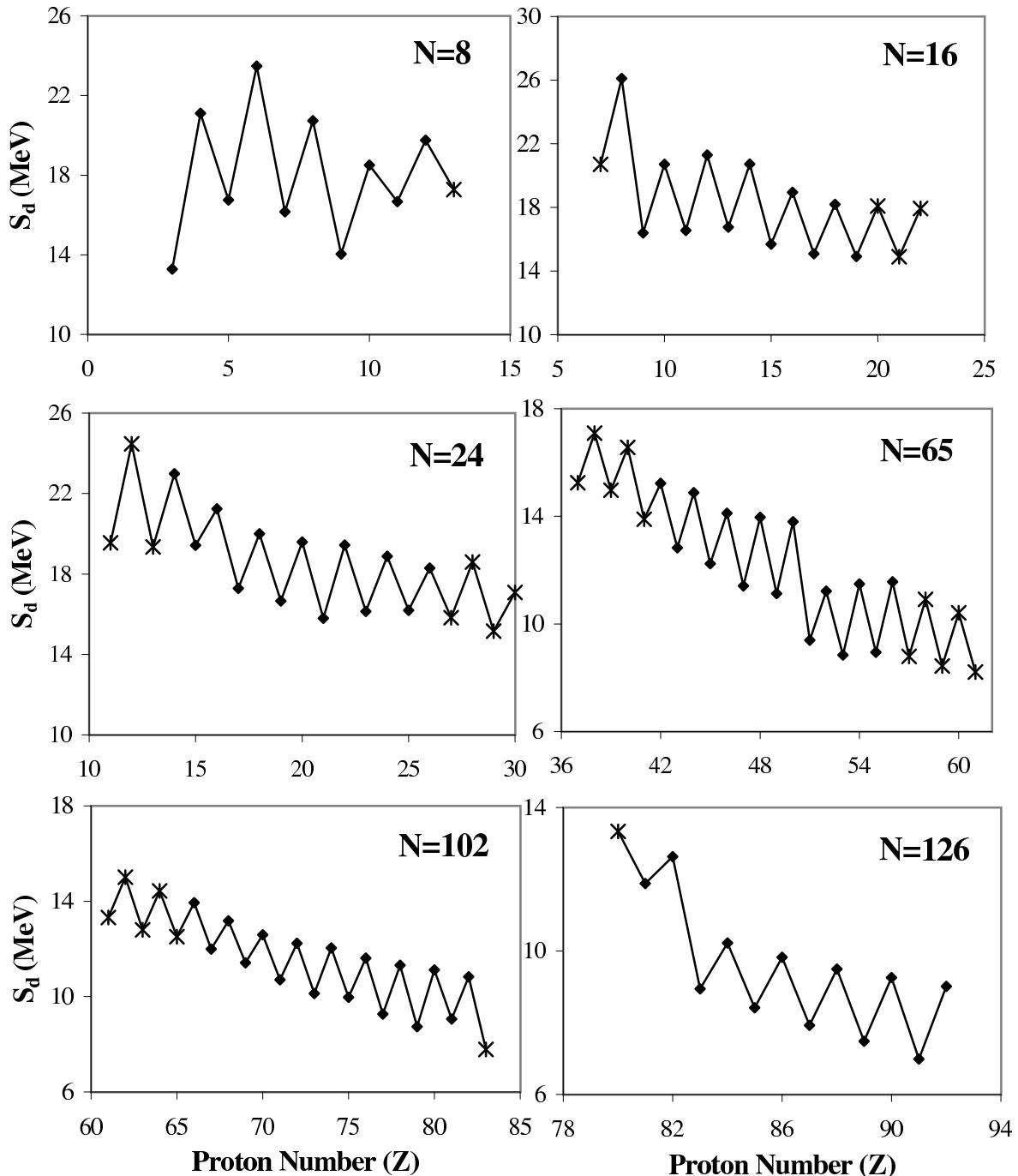


Figure 2: Same as Fig.1 except against proton numbers at specific neutron numbers.

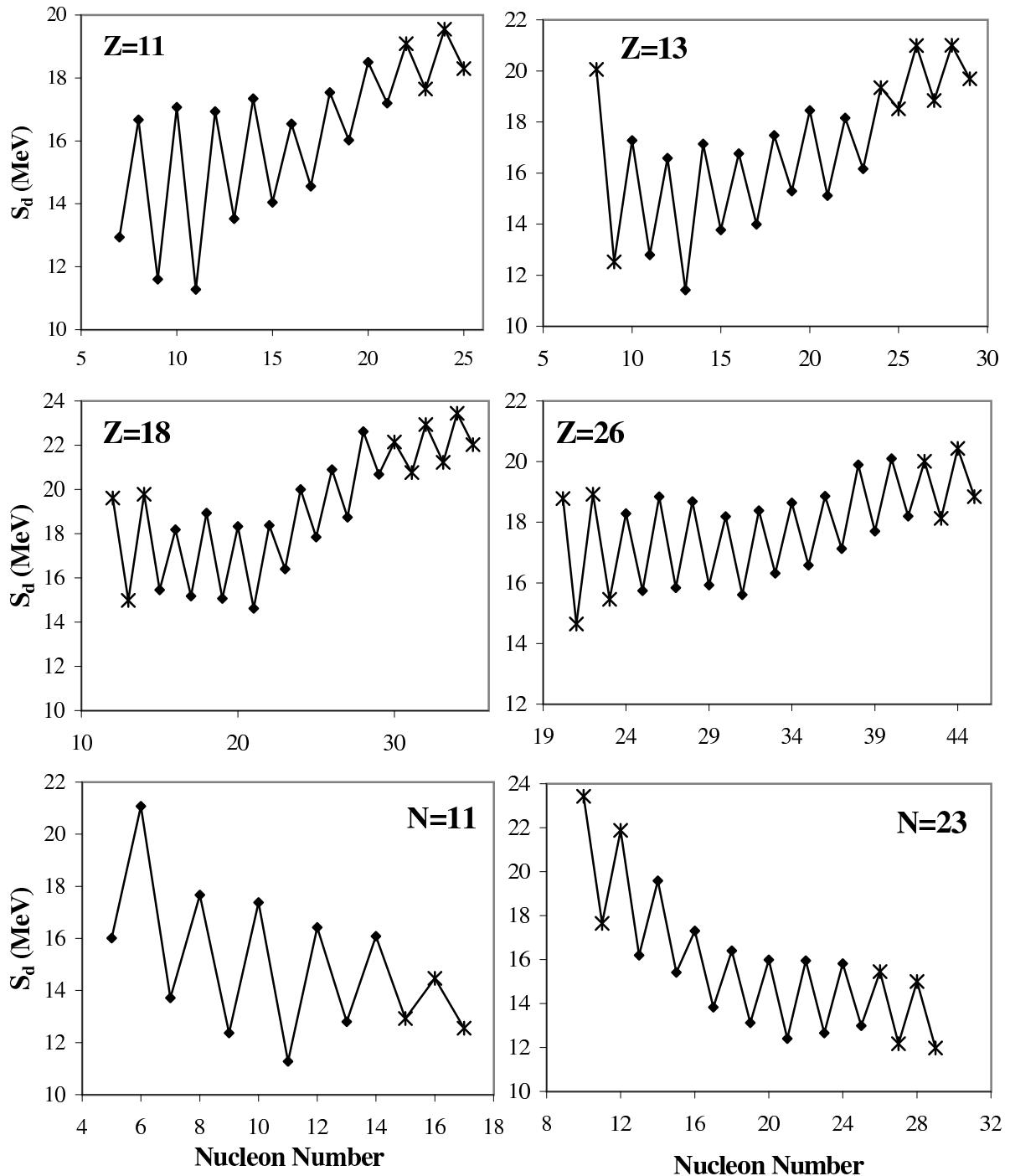


Figure 3: Same as Fig.1 except against nucleon numbers (proton or neutron numbers).

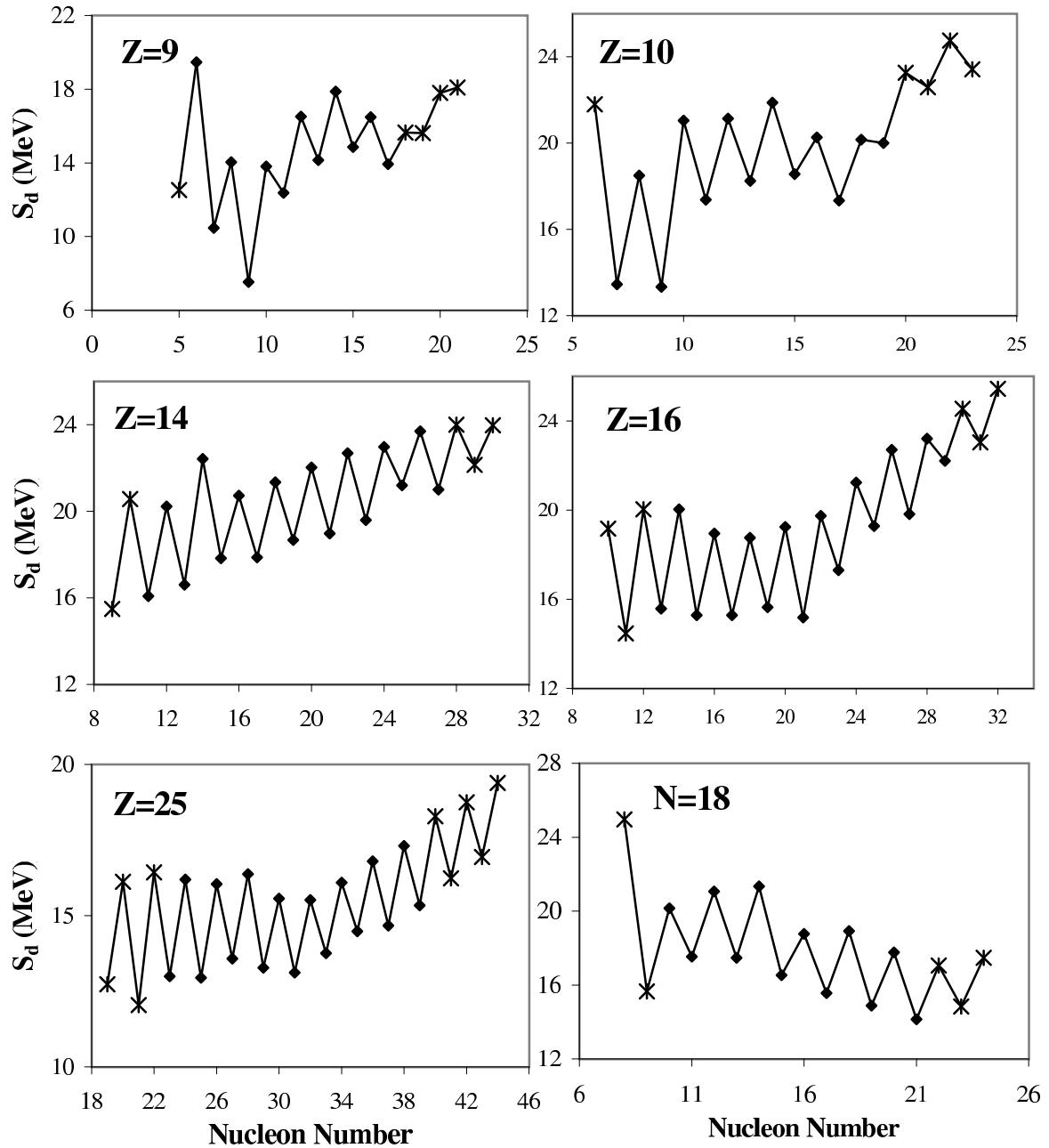


Figure 4: Same as Fig.3.